“An Open-Circuit and a Short-Circuit in the Pacific Ocean Subtropical-Tropical Exchange”

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ABSTRACT

The origin and pathway of water occupying the surface layer of the eastern Equatorial Pacific (“Nino3”) are investigated using circulation estimates of the ECCO Ocean Data Assimilation System. The water mass is tracked by a passive tracer and its adjoint that, respectively, describe where the water goes to and where the water comes from. Water originates in the eastern subtropics but returns to the western subtropics (an “open-circuit”). Intra-seasonal variability significantly alters the pathway by stirring the water masses, “short-circuiting” the meridional circulation.

Introduction

Subtropical-tropical exchange has been identified as a possible mechanism underlying prolonged El Niño conditions in the early 1990s and other interdecadal fluctuations of the tropical Pacific Ocean [5]. In this scenario, anomalous water subducted in the subtropics is advected over a decade to low latitudes changing the equatorial thermal structure and thereby affecting sea surface temperature and consequently El Niño. Here, we examine this hypothesis focusing on the origin and pathway of the water mass occupying the surface layer within “Nino3” (150°W~90°W, 5°N~5°S), a region central to El Niño.

General Circulation

The “Subtropical Cell” [STC; 6] describes the average meridional exchange (Fig 1 left). Water that reaches the tropics originates in the eastern subtropics (Fig 1 right), most of which flows via the low latitude western boundary currents (Mindanao Current, New Guinea Coastal Undercurrent). However, observed passive tracer distribution suggests that the interior pathway may be the dominant component instead. For instance, maximum values of tritium along the equator is found in the central Pacific instead of the western end (Fig 2; [2, 3]). Although thermal anomalies have also been traced from the subtropics towards the equator [1], coherence is lost within the tropics, raising questions to the significance of the STC [8].

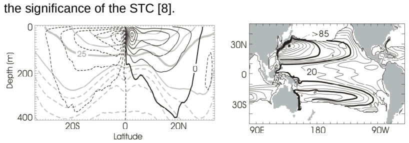

Fig 1: ECCO Mean Circulation Estimate.
(Left) Zonally integrated meridional transport stream function in the Pacific Ocean (“Subtropical Cell”). Contour intervals are 5 Sv. [Negative values in dashed.] Grey curves are potential density (c.i. of 1 [solid] and 0.2 [dashed] kg/m³) (Right) Bernoulli function along the thermocline (25.0 kg/m³ potential density surface). Units are in equivalent sea level (cm).

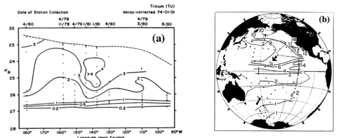

Fig 2: Decay-Corrected Tritium Distribution (from Fine et al, 1981, 1987 [2, 3])
(Left) Tritium concentration along the equator vs depth (density).
(Right) Tritium concentration on 23.9 kg/m^3 potential density surface.

Passive Tracer and Its Adjoint

A passive tracer can be utilized to track the circulation of a body of water;

$$\partial c/\partial t = -\vec{\mathbf{u}}\cdot\nabla c + \nabla\cdot(\kappa\nabla c) \qquad (1)$$

By using the same numerical algorithm, velocity field $\vec{\mathbf{u}}$, and mixing tensor κ that operate on temperature and salinity, the tracer ***c*** uniquely follows the advection and mixing of the water mass that the tracer occupies (Fig 3). In particular, the evolution of tracer ***c*** describes ***where the water goes to***.

The adjoint of the tracer, ***c'***, describes ***where the water comes from***. This can be understood by considering the sensitivity of a passive tracer content within the water volume to tracer distribution in the past. A sensitivity would exist only for locations where some of its water makes its way to the target volume. This sensitivity can be identified as the adjoint of the tracer. For instance, consider the sensitivity of tracer content at a particular location *i* at a particular time *T;*

$$J = \sum_x e_i^T c(T) \qquad (2)$$

where $e_i = 0$ except $e_i = 1$ at location *i*. The sensitivity of *J* to tracer distribution *N* time-steps in the past $c'(T-N)$ is,

$$c'(T-N) \equiv \frac{\partial J}{\partial c(T-N)} = \frac{\partial c(T-N+1)^T}{\partial c(T-N)}\frac{\partial c(T-N+2)^T}{\partial c(T-N+1)}\cdots\frac{\partial c(T)^T}{\partial c(T-1)}\frac{\partial J}{\partial c(T)} \qquad (3)$$

where $\partial J/\partial c(T) \equiv c'(T) = e_i$. Eq (1) in finite difference form may be written as $c(t) = \mathbf{A}(t-1)c(t-1)$ Then, $\partial c(t)^T/\partial c(t-1) = \mathbf{A}^T(t-1)$ etc and (3) may be written as,

$$c'(T-N) \equiv \partial J/\partial c(T-N) = \mathbf{A}^T(T-N)\mathbf{A}^T(T-N+1)\cdots\mathbf{A}^T(T-1)e_i \qquad (4)$$

The operations conducted from right to left $c'(t-1) = \mathbf{A}^T(t-1)c'(t)$ etc define the adjoint, and in continuous form can be written as

$$-\partial c'/\partial t = +\vec{\mathbf{u}}\cdot\nabla c' + \nabla\cdot(\kappa\nabla c') \qquad (5)$$

The sensitivity, Eq (3), is obtained by integrating (5) backwards in time from time *T*, with terminal condition $c'(T) = e_i$.

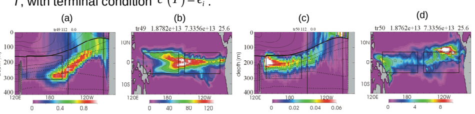

Fig 3: Testing Passive Tracer (a, b) and Its Adjoint (c, d)
The origin of water in Nino3 (top 10m) on 31 Dec. 2000 is examined using a passive tracer (left) and adjoint tracer (right), respectively integrated by the ECCO circulation estimates. The passive tracer is released 1 Jan 2000 in the thermocline in the western equatorial Pacific (140°E~160°W, 5°N~5°S, 150~300m). The adjoint tracer is initialized in Nino3 on 31 Dec 2000. Both tracers are initialized to unity (in arbitrary tracer unit; ATU). Figures show zonal sections (a, c) and depth-integrated plan views (b, d) for the respective results after a 1-year integration. Both results show that 25.6% of the Nino3 water originated from the western equatorial thermocline 1-year prior.

Origin, Pathway, and Destination of Nino3 Water

The adjoint (5) and the forward (1) passive tracer equations are integrated in time to deduce where Nino3 water comes from and where it goes to. The two equations are initialized with uniform tracer distributions in Nino3 (unit ATU within the surface 10m) and are integrated using ECCO circulation estimates [4]. Unless otherwise noted, tracers below are averages sorted by time among separate integrations initialized at the end of different years between 1980-2000.

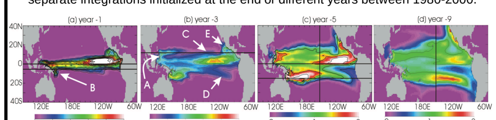

Fig 4: Column Integrated Nino3 Adjoint Tracer (ATU/m²) at Different Times

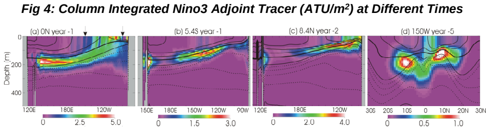

Fig 5: Select Vertical Sections (10⁻² ATU/m³) of Fig 3 at Different Times
Contours are potential density (C.I.=1 kg/m³; thick curve is σ=25 kg/m³).

Discussion

Nino3 water travels distinct pathways from the western equatorial Pacific and from away from the equator (Fig 4). The circulation in the interior and low latitude western boundary currents (LLWBCs) are largely confined to within the thermocline (Fig 5), whereas the coastal pathway mostly resides at the surface. In each hemisphere, the LLWBCs carry 70~80% of the meridional transport (Table 1). On average, nearly 30% more of the Nino3 water originate from the southern hemisphere than the northern hemisphere.

Mean transit times (mode) between the subtropics and Nino3 is about 10-years (Fig 6). Approximately 16% of the Nino3 water is found in the surface mixed-layer 10-years prior in nearly equal amounts in the eastern basin of each hemisphere (Fig 6).

Intra-seasonal variability stirs the water mass, resulting in a much larger interior transport than the pathway inferred from either seasonally averaged or time-mean circulations (Fig 7, Table 1).

Fig 8 elucidates the “sloshing” of the thermocline associated with the ‘97-’98 El Niño that is in contrast to other years (Figs 3, 4, 5). In particular, the western end of the water mass coincides with the movement of the 28°C isotherm [7].

The strength of the thermocline exchange weakened during the 1990s (Fig 9).

The forward passive tracer (Fig 10) shows Nino3 water leaving westward away from the equator to the subtropics, above the pathway towards Nino3 identified by the adjoint tracer (Fig 5). However, its destination is not the original subduction region; the subtropical-tropical exchange does not close even after 80-yrs (Fig 11).

Latitude	Experiment	Total	LLWBC	Interior	CRD
5.7ºS	Average	-29.0 [-38%]	-23.0 (79%)	-6.0 (21%)	
	Steady	-30.0 [-39%]	-27.9 (93%)	-2.2 (7%)	
	Seasonal	-30.1 [-39%]	-27.0 (90%)	-3.1 (10%)	
8.4ºN	Average	21.9 [29%]	15.8 (72%)	4.0 (18%)	2.1 (10%)
	Steady	16.7 [22%]	17.3 (104%)	-0.1 (0%)	-0.6 (-3%)
	Seasonal	20.3 [26%]	19.5 (96%)	1.4 (7%)	-0.6 (-3%)

Table 1: Net 10-year Meridional Transport of Nino3 Adjoint Tracer (10^{12} ATU)
Positive values indicate northward transport backwards in time. Percentages in parentheses are those of each total transport across the section. Values in brackets in the total column are percentages of the global net adjoint tracer.

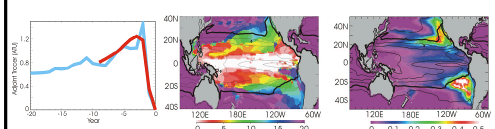

Fig 6: Time-series of Adjoint Tracer at 156E, 11N (left), Transit Time Mode of Column Integrated Adjoint Tracer (years) (middle), and Adjoint Tracer within the Mixed Layer at Year -10 (ATU/m²) (right).
Contours are surface potential density (C.I.=1 kg/m³; thick curve is σ=25 kg/m³).

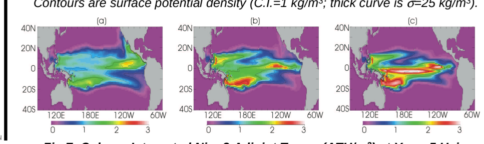

Fig 7: Column Integrated Nino3 Adjoint Tracer (ATU/m²) at Year -5 Using Different Circulation Fields.
Average distribution (a), seasonal circulation (b), time-mean circulation (c).

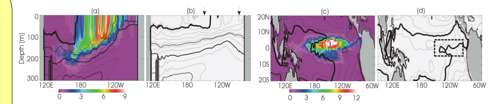

Fig 8: Zonal Section (a) (ATU/m³) and Column Integrated Nino3 Adjoint Tracer (c) (ATU/m²) 1-year Prior Starting from 31 Dec 1997. *Contours are temperature (c.i.=1°C, thick curve is 28 °C). Contours in right panels are SST. Also shown are temperature section (b) and SST (d) of 31 Dec 1997.*

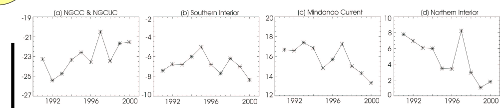

Fig 9: Net 10-year meridional transport of Nino3 adjoint tracer as a function of terminal instant. *Units in 10^{12} ATU. New Guinea Coastal Undercurrent (a), southern hemisphere interior pathway (b), Mindanao Current (c), and northern hemisphere interior pathway (d).*

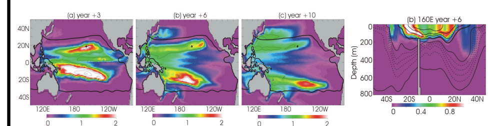

Fig 10: Column Integrated Nino3 Passive Tracer (ATU/m²) and Meridional Section (ATU/m³)

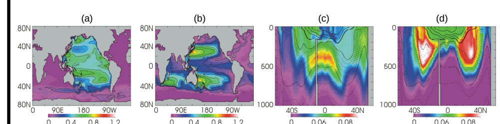

Fig 11: Tracers at year -40/+40. *Column integrated adjoint tracer (a) and forward tracer (b) (in ATU/m²), and their meridional cross sections along 160E (c & d, respectively) (in ATU/m³) at year -40 and +40, respectively.*

Conclusion

Subtropical-tropical mass exchange is investigated using a simulated passive tracer and its adjoint. Unlike float trajectories, tracers reflect effects of both advection and mixing (including convection), and their evolution is not chaotic.

Nearly 80% of the subtropical water mass reaching Nino3 travel via the low latitude western boundary currents. The remaining 20% directly reaches the tropics by the interior pathway. Transit times are approximately 10-years.

Intra-seasonal variability significantly alters the mean water pathway. In particular, inferences made by seasonal and/or time-mean circulation significantly underestimates the magnitude of the interior pathways. The tracer evolution suggests that the “Subtropical Cell” is not a closed circulation.

References

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Acknowledgement

This is a contribution of ECCO funded by National Oceanographic Partnership Program. This research was carried out in part at JPL/Caltech under contract with NASA.